Scenarios for the Expanded Use of Nuclear Energy

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Abstract – Interest in the use of nuclear energy beyond the traditional electricity sector has grown into other energy markets. In particular, the potential use of nuclear energy for hydrogen production has generated significant interest. Hydrogen is being investigated as a clean and secure alternative to gasoline as a transportation fuel, and nuclear-produced hydrogen offers substantial environmental and energy security benefits. Nuclear energy may also have a future role to play in the desalination or decontamination of water to address the growing world issue of clean water availability.

This paper analyzes different nuclear energy systems development scenarios for nuclear energy delivering a significant part of the electricity and hydrogen demand on world scale. Delivering these vast amounts of energy is shown to be feasible using a combination of thermal, high-temperature and fast reactor systems. The use of symbiosis among the different reactors in a closed fuel cycle system limits the required geological repository space and the transuranic inventory in the fuel cycle. Only a modest cost increase, over the cost of existing once-thru fuel cycle, will be needed to achieve such a sustainable nuclear energy system delivering vast amounts of electricity and hydrogen.

I. INTRODUCTION

The role of nuclear power in today's and future energy generation market is subject of many debates. Proponents of nuclear power base their arguments on the very good safety record, economic performance and especially the environmental benign nature of nuclear energy avoiding green-house gas emissions. Opponents defend their position in highlighting the perceived absence of a long-term waste management solution, the disputable safety aspects of nuclear reactors, the potential for proliferation of nuclear materials and the poor economics. Objectivity is essentially lost in these debates.

If nuclear energy will have to serve a growing energy demand, nuclear energy has to respond to the issues subject of these socio-political debates [1]. As this paper will show once again, nuclear energy is capable of delivering vast amounts of sustainable energy for the world if the following objectives are realized:

- *Cap the amount of spent fuel arising* and needing geological disposal. Today's existing nuclear park will produce up to about 600,000 tHM spent fuel by around mid century. Closed fuel cycles allow a great deal more energy to be produced while keeping the amount of spent fuel or waste much lower than this 600,000 tHM.
- *Minimize the volume of repository space for each additional TWhe energy produced.* While the need for geologic repository is not avoided, optimal use of repository space is a necessity for any future nuclear energy deployment.
- *Make nuclear energy economically attractive.* Limit the additional costs for advanced nuclear energy systems and keep the forward-going costs as low as possible.
- *Optimal use of scarce resources.* Make best use of available natural uranium and thorium by extracting maximal energy from the mined material.
- *Serve the different energy markets.* Large and small nuclear plants will be needed using different technologies, i.e. temperature ranges, to serve the various demands ranging from electricity up to hydrogen generation in different market conditions.
- *Manage non-proliferation concerns.* The projected deployment of nuclear energy will only be possible if the socio-political concern of non-proliferation can be inherently solved by designing the advanced nuclear energy systems to be non-proliferant and/or under the auspices of international regional fuel cycle centers.
- *Drastically reduce the long-term stewardship of waste.* While this goal may not be the main objective, a drastic reduction of the potential radiotoxicity in the waste may be achieved by changes in the composition possibly relaxing the

socio-political concerns about such long-term disposal plans.

These goals can be achieved by nuclear energy through the use of recycling (i.e. cap the amount of waste), removing the transuranic actinides from waste (i.e. minimize volume of repository space per TWhe and reduce stewardship period), and by the deployment of a symbiotic mix of nuclear reactor types serving the different energy demands in addition to allocation of the fissile materials for maximum added value on those reactors [1,2]. Finally, the deployment of regional fuel cycle centers on world-scale is probably crucial to achieve a secure, competitive and truly sustainable nuclear energy system serving the energy needs of our society for the coming centuries [3].

These objectives have been used to analyze potential nuclear energy demand scenarios on world scale. The remainder of this paper will first address the energy demand scenarios considered, the waste arising and the needed deployment of fuel cycle services, and will finally address the economics of such systems.

II. ENERGY DEMAND

Electricity generation has been for a long time the main reason to deploy nuclear plants. Today, the ever increasing energy demand and shifts among different energy carriers (electricity, gas, hydrogen,…) ask for a wider spectrum of energy vectors that may be addressed by nuclear energy. The five major energy vectors of interest here are electricity, district heating, water desalination, process heat and hydrogen production. The following is a discussion of the global energy demand considered in this paper and the possible contribution of nuclear energy to the fulfillment of this future demand.

II.A. Electricity

Several studies by authoritative agencies have been published in the past years projecting the possible demands for electricity and the part generated by nuclear plants. In this paper, use was made of the projections published in 'Scenarios of Nuclear Power Growth in the 21st Century' [4] which was based on a review of the different scenarios performed by IIASA/WEC [5,6], IAEA [7,8] and OECD/IEA and NEA [9,10]. The study examined specifically two contrasting scenarios of overall energy demand. The first scenario is referred to as 'business-as-usual' (BAU), and assumes that future energy demand growth will not be governed by policy measures aiming specifically towards protecting the environment. The second energy demand scenario, referred to as 'ecologically driven' (ED), takes the contrasting view that specific environmental protection measures will be implemented aiming towards reducing the risks of global warming. For each of these two energy demand scenarios, two contrasting scenarios for nuclear power were considered. The first nuclear scenario, referred to as 'basic option' (BO), assumes that growth in nuclear electricity production will be driven by economic competitiveness of nuclear power in comparison with other electricity generation options (see reference [4] for more details). The second scenario for nuclear power, referred to as the 'phase out' (PO), assumes that nuclear power will be essentially phased out of electricity generation by around the middle of this century, irrespective of its economic competitiveness, driven by national decisions to turn away from nuclear power. For this analysis, the BAU-BO scenario was taken according to a low and a high variant as reported in [11].

II.B. Non-Electrical Energy

District heating

The use of district heating is today a practice in essentially Central European countries and is mostly based on a cogeneration mode. Usually, district heating systems are supplied with hot water and steam, the typical temperature range being 100-150 °C. The heat source and distribution network, usually including a steam-water heat exchanger between the supplier and customer, must be designed accordingly. The typical heat generation capacities for district heating are defined by the size of the customer. The capacity of heat networks in large cities can be assessed as 600-1200 MWth but it is much smaller in towns and smaller communities, e.g. 10-50 MWth. Large capacities, i.e. 3000-4000 MWth, are exceptional.

The market for district heating is defined by the availability of heat distribution networks and the competition between different energy carriers, i.e. gas heating, heating by electricity, etc. The market potential for nuclear energy delivering district heating is also conditioned by the need to site the heat source, i.e. nuclear plant, close to the final customers which will need a high degree of confidence by those customers in the safety of such nuclear plants.

Based on such market and technological considerations, reference [12] projected a low and high estimate for the energy demand for district heating for different world regions and the fraction that might be delivered by nuclear energy. Only about 5% of the district heating demand was considered to be delivered by nuclear energy with total district heating demand growing by some 1.5%/yr.

Process heat

Process heat is mostly delivered as part of a cogeneration plant for electricity and heat production. The analysis in [12] confirmed this and made also an assessment of the energy demand for such process heat applications. Due to this cogeneration mode approach, and due to the rather limited market compared to the electricity and potential hydrogen market (see later), the nuclear energy demand for such process heat applications was assumed to be integrated in the previous electricity demand assessment.

Water desalination

Based on an analogous methodology as for district heating reference [12] includes a qualitative assessment of the potential energy demand for water desalination purposes. While the need for energy for water desalination can be very significant, the market potential for nuclear energy may be rather limited due to technological and economical considerations [12]. The capacity range for nuclear power plants for such desalination purposes is essentially defined by the processes used for this desalination. Heat, usually in the form of steam at some 100-130 °C is needed for distillation processes, electricity is needed as primary energy source for reverse osmosis processes and as energy for pumping in MSF and multi-effect distillation MED processes. For this analysis, growth rates of 2 and 4 %/yr for the desalination demand in different world regions was assumed where nuclear might deliver 15% of this demand.

Hydrogen production

Hydrogen production has been the main market niche addressed in recent studies on future innovative nuclear energy use. Several studies have been undertaken or are under consideration assess market potential for hydrogen in several economic sectors and especially the role that nuclear energy may play [13,14]. Also the IIASA/WEC study delivered an assessment of the hydrogen demand for this century [6]. Based on these data, a combined hydrogen energy demand scenario was derived.

The future hydrogen market is perceived as quite speculative. Several studies are undertaken to analyze the potential market penetration of hydrogen in different fields of application, e.g. transport and decentralized energy delivery. Today's knowledge of hydrogen production, storage and distribution technologies indicate that most probably the market penetration of hydrogen will pass through a phase with large production plants delivering the hydrogen product to final users through pipelines or truck delivery depending on final daily usage of hydrogen. Such a hydrogen production and delivery topology favors large nuclear power plants (NPP) operating as regional hydrogen production plants. For this analysis, two scenarios were assumed differing in the fraction of hydrogen generation by nuclear energy, i.e. 20% and 50%.

II.C. Global Energy Demand

Based on these assumptions, a global energy demand for nuclear energy was derived and shown in Figure 1. In this figure, three nuclear energy demand scenarios are defined, i.e.:

- 'Low' corresponding to the sum of the low estimates for nuclear energy demand for the different energy vectors;
- 'Middle' corresponding to the sum of low estimates for electricity, district heating and water desalination plus the high estimate for hydrogen production nuclear energy demand needs; and
- 'High' corresponding to the sum of all high estimates for the nuclear energy demand for the different energy vectors.

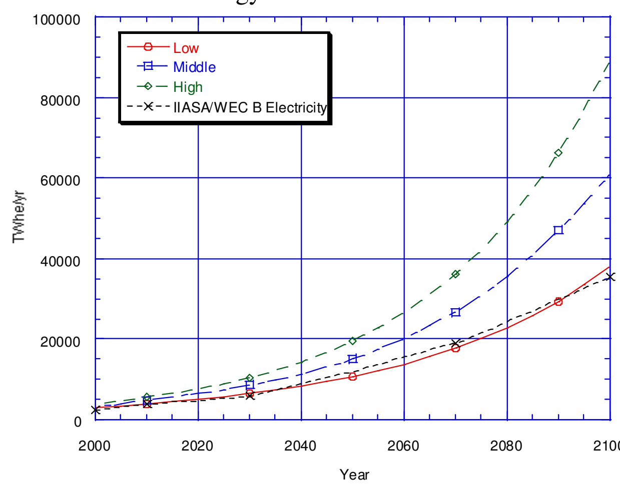

Fig. 1. Global Nuclear Energy Demand Scenario Used in this Paper.

Figure 1 also shows the IIASA/WEC scenario B nuclear energy demand for electricity purposes as a kind of reference scenario (define scenario B) [6]. The 'Low' scenario clearly represents a lower bound estimate for nuclear energy demand in business-as-usual cases. The 'Middle' scenario represents an initially scenario B (IIASA/WEC) demand where hydrogen production starts to add nuclear energy demand from mid century on. Finally, scenario 'High' represents an ambitious nuclear energy demand development reaching 90,000 TWhe/yr by the end of this century to be compared to today 2500 TWhe/yr. More details about the assumptions taken in these scenarios are given in [11]. The decomposition for the middle energy demand scenario is shown in Figure 2 indicating the potential importance of the new hydrogen generation demand.

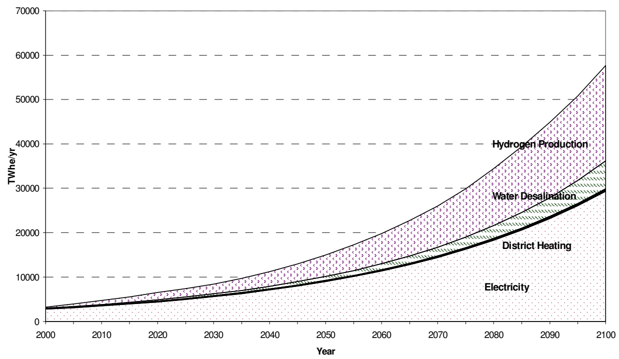

Fig. 2. Global Nuclear Energy Demand Decomposed According to Energy Service Sector for Middle Energy Demand Scenario.

Some words of caution with respect to these energy demand projections are worthwhile. The potential for nuclear energy in non-electrical applications seems promising, but the development from dreams to reality will take time. Many social, economic and technological hurdles will have to be resolved before these non-electrical applications for nuclear energy may come true. Safety implications of coupling NPPs to high-temperature processes or hydrogen production facilities will demand in-depth studies and additional technological developments. Especially the (inherent) safety performance of such NPPs, closely sited to chemical plants or even cities, will have to be proven. The smaller size NPPs needed for district heating and process heat need still to be economically viable, i.e. the balancing of economies of production versus economies of scale will be necessary. Finally, public acceptance for a growing use of NPPs will have to be handled especially if smaller-size NPPs are proposed for operation in close vicinity of densely populated areas.

The question which arises now is how nuclear energy might be able to deliver such vast amounts of energy while achieving the objectives as stated above. The nuclear energy system strategies considered in this paper are representative for the main strategies one may envisage for such a nuclear energy deployment and are pictured in Figure 3, i.e.:

- once-through operation of light water reactors (LWRs)
- Pu mono-recycling in LWRs, so-called 'mono-MOX'
- Pu mono-recycling in LWRs with the MOX-fuel being reprocessed and the transuranics (TRU) sent to TRU-burning in fast reactors (FRs) with conversion ratio of 0.50, so-called 'LWR+MOX+FR'.
- LWRs with TRUs are sent to FR burners (conversion ratio 0.5), so-called 'LWR+FR'

Gas-cooled high-temperature reactors (HTGRs) are an important alternative for LWRs in this respect and were only considered in the once-through strategies. Further analysis is being performed in using such HTGRs as Pu-burners in partial and full recycle strategies.

The attributes for the different reactors and fuel cycle facilities were analogous to the scenario analysis done using the DYMOND and DANESS-codes and reported in references [1,15,16] and shown in Table 1.

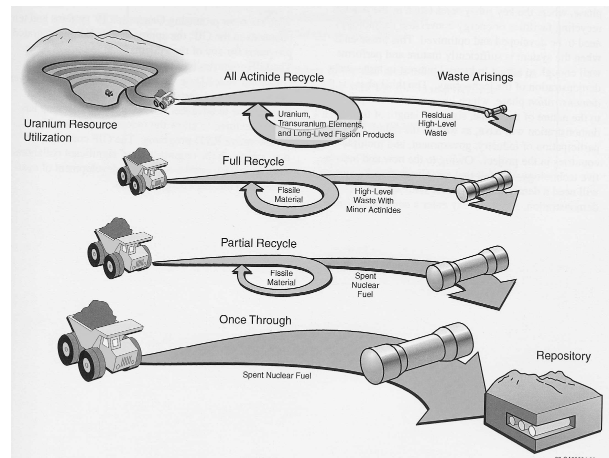

Fig. 3. Nuclear Energy System Strategies Considered in this Paper [1].

III. SYSTEMS ANALYSIS

The availability of uranium has been analyzed by many studies in the past with sometimes conflicting conclusions depending on the scope taken by the study [17,18,19]. Estimations of uranium resources, e.g. by IAEA/NEA, show that based on today's knowledge of expected resources enough uranium would be available to feed the existing reactor park for the coming century. If nuclear energy deployment would grow according to the estimates in Figure 1 shown scenarios, these expected resources would get depleted by around mid-century as was also shown by the analysis performed in the Generation-IV roadmap study [1]. After mid-century, the required rate of discovery and harvesting of new uranium ore reserves should have to grow steadily from half a million tones per year to almost two million tones per year by 2100 and reaches a cumulative total (known plus speculative plus new discoveries) uranium consumption of some 57 million tones by 2100 (for the mid energy demand scenario in Figure 1).

Table 1. Reactor and Fuel Attributes

Reactors	PWR	BWR	ALWR		HTGR	FR (CR=0.5)
Thermal Power (MWth)	2647	2647	2647		600	843
Electric Power (MWe)	900	900	900		284	320
Thermal Efficiency (%)	34	34	34		47	38
Capacity Factor (%)	90	90	90		90	85
Technical lifetime (yr)	50	50	50		50	50
Fuels						
	UOX	UOX	UOX		MOX	Particle
Average Burnup (GWd/tHM)	50	40	50	50	120	Metal
# fuel batches	5	5	5	3	7	120
Cycle length (mo)	12	12	12		12	12
Initial U (t/tIHM)	1	1	1		0	1
Initial enrichment (%)	4.2	3.7	4.2	0.25	15.5	0
Initial DU (t/tIHM)	0	0	0	0.91903	0	
Initial REPU (t/tIHM)	0	0	0	0	0	0.061
Initial Pu (t/tIHM)	0	0	0	0.08097	0	0.5936
Initial MA (t/tIHM)	0	0	0	0	0	0.2919
Spent U (t/tIHM)	0.93545	0.94576	0.93545	0.88753	0.85917	0.0535
Spent enrichment (%)	0.82	0.8	0.82	0.15	4.8	0.5936
Spent Pu (t/tIHM)	0.012	0.1085	0.012	0.05512	0.01883	
Spent MA (t/tIHM)	0.00125	0.00114	0.00125	0.0074	0.002	0.2365
Spent FP (t/tIHM)	0.0513	0.04225	0.0513	0.04996	0.12	0.0452

Despite these sometimes announced finite resource estimations, there is currently no objective reason indicating that a new exploration effort will not result in additional resources in amounts well beyond the current estimates of speculative resources. The price of such uranium may temporarily increase compared to today's 30 \$/kgUnat. The price will be dictated by the supply/demand balance with the possibility that the price increase will be limited because of new technology and exploration [20]. In this case, natural uranium might not be a limiting resource for nuclear power in the foreseeable future although the price of such uranium might be increasing.

While the availability of natural uranium resources might not be the limitation to nuclear energy deployment the availability of repository space will. Figure 4 shows the amount of waste in the world to be deposited for the various nuclear energy system strategies and this for the low energy demand scenario. Continuation of (essentially) today's once-through fuel cycle scenario in LWRs would result in more than 3 million tones of spent fuel (SF) to be disposed of by end of this century. This would even become almost 6 million tones of SF in the high energy demand case. Reprocessing of the waste and using the reprocessed fissile materials in LWRs as well as in HTGRs or FRs may appreciably reduce this amount of waste by at least a factor of 30 as shown in Figure 4.

The amount of transuranics (TRUs) residing in the fuel cycle, i.e. out-of-pile and out-of-repository, depends on the composition of reactor type present in the nuclear reactor park as shown in Figure 5 (again for the low energy demand scenario).

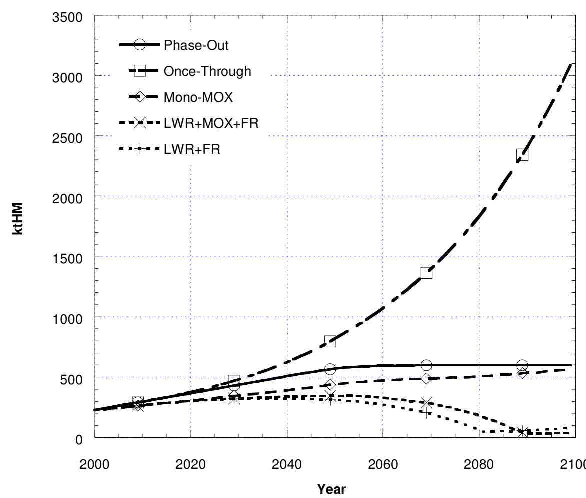

Fig. 4. Global Amount of Waste Arising from Different Nuclear Energy Systems

The same behavior occurs for the high energy demand scenario except that it will be scaled by a factor of 2, i.e. up to about 90,000 tHM TRUs out-of-pile by 2100. This effect of burning the TRUs is also shown in Figures 6 and 7 giving the cumulative heat load from all waste, at a certain moment in time, which might be sent to repositories according to the different energy system strategies. This heat load is calculated as the cumulative amount of heat generated by spent fuel and/or high level waste (HLW) between 100 years and 1500 years after the spent fuel had been discharged from the reactor. While the HLW is always deposited in repositories, these heat loads also include the contribution from spent fuel residing in the fuel cycle before disposal or reprocessing, i.e. in interim storage. These calculations are based on the results presented in reference [21] (more details about the heat load calculations are described in reference [22]). Figure 6 shows the results for the low energy scenario while Figure 7 shows the results for the high energy demand scenario.

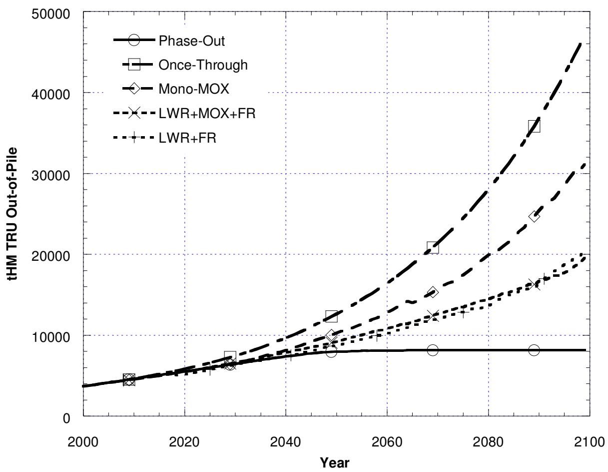

Fig. 5. Amount of TRUs Out-of-Pile for the Low Energy Demand Scenario.

These results clearly show the importance of reprocessing and burning the TRUs in appropriate reactors. Using fast reactors, an important reduction can be achieved in the cumulative heat to be removed from the geological repositories. This also means that the repository space may be better used, i.e. more compact packing of the waste canisters and thus achieving the objective of minimizing the volume of repository space needed per additional TWhe generated. Figures 5, 6, and 7 also show the limited importance of a LWR-MOX phase from the perspective of temperature-limited repositories. Despite some reduction in the amount of waste, the decay heat of the remaining MOX SF is higher due to the buildup of higher amounts of TRUs which counters the benefits of lower waste volumes. Such a decrease in decay heat of the waste deposited in repositories can result in a reduction of the repository size especially if some longer decay time is used before emplacing the waste canisters in the repository (decay of short-lived fission products) [21].

These scenario results show that nuclear energy systems can deliver vast amounts of energy to society while minimizing the impact on the environment. First, greenhouse gas emissions can be avoided. Moreover, the last three figures show that the repository heat load (related to the size of a thermally constrained repository) that corresponds to the growth scenarios can be only 2 to 3 times the heat load corresponding to a phase-out scenario if the advanced nuclear energy systems are used. Notice that up to twenty-fold more energy will be generated from the growth scenarios compared to the phase-out scenario. In addition, the lower amount and more active TRUs residing in the fuel cycle are positive attributes with regard to non-proliferation and, when coordinated through regional fuel cycle centers, it would be non amenable to diversion.

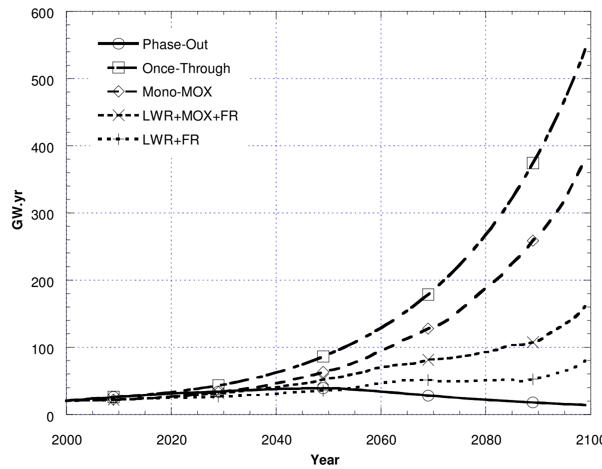

Fig. 6. Cumulative Heat-Load(GW_{th}.yr) in Repository by the Waste Emerging from Different Nuclear Energy Systems for the Low Energy Demand Scenario.

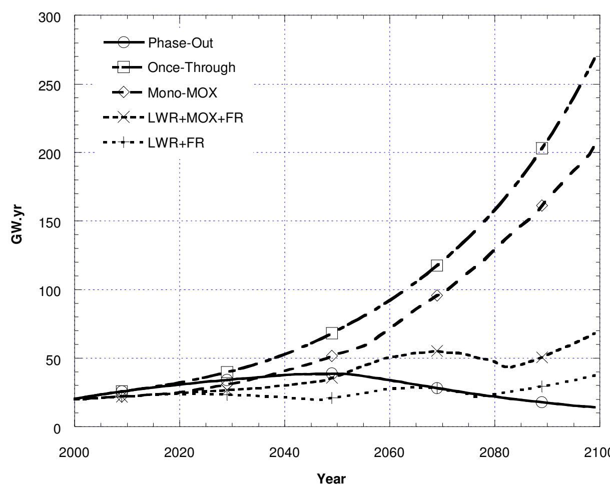

Fig. 7. Cumulative Heat-Load(GW_{th}.yr) in Repository by the Waste Emerging from Different Nuclear Energy Systems for the High Energy Demand Scenario

The limitation of the amount of waste to be disposed of as well as the size of the fuel cycle enterprise, i.e. up to about 140 000 tHM reprocessing capacity in the high energy demand scenario, likely requires a certain consolidation of these activities in a limited number of regional fuel cycle centers worldwide. Each fuel cycle center could then serve the regional market in back-end services, i.e. from SF-handling through reprocessing and re-fabrication up to waste disposal [3].

IV. ECONOMICS

The economic performance of symbiotic nuclear energy systems compared to non-nuclear energy systems will define the viability of such nuclear energy systems. Figure 8 shows this comparison based on total energy costs with and without external costing taken into account. The economic data used in this economic evaluation are identical to those used in reference [15]. The gas-fired station economics is based on today's technology.

The additional costs for advanced nuclear energy systems displayed in this paper should, however, be compared to the full cost of generating energy by other means, when including externalities. For example, the cost of carbon dioxide sequestration is estimated to be 1.5 cents per kWhe for gas-fired plants and 2-3 cents per kWhe for coal-fired plants in the US [22]. The ExterNe-study by the EC also showed that the external costs for coal and gas-based electricity production amounts to 2 – 15 and 1 – 4 euro-cents per kWhe, respectively, compared to 0.2 – 0.7 euro-cents per kWhe for nuclear energy [23]. Thus, taking into account this external cost can make the nuclear energy systems competitive as shown in Figure 8.

In addition to the effect of including external costs, price volatility as a function of fuel price can be important to the competitiveness of nuclear energy as it is expected to be much less for nuclear than for fossil energy resources, especially gas. Finally, Figure 8 shows that the resource longevity and waste reduction advantages that can be achieved through recycling would require modest cost increases that can be limited to about 15% compared to the once-through fuel cycle.

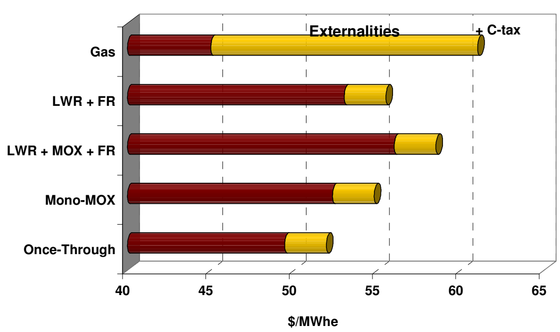

Fig. 8. Economics of Nuclear Energy Systems.

V. CONCLUSIONS

Nuclear energy systems based on closed fuel cycles may be designed to serve different energy markets and may generate large increases of energy while remaining economically and environmentally benign. Substantial decrease in the volume/mass of the waste destined to geological repository can be achieved by such advanced nuclear energy systems. In the case of a nuclear park utilizing advanced system (for thermally constrained repositories), the needed repository space in a growing nuclear energy scenario will be only 2 to 3 times the size of the repository needed to store the waste from the phase-out of the existing nuclear park. Notice that the energy generated in this growth scenario can be up to twenty fold the energy generated from the phase out case. In addition, an improved waste management policy may be developed allowing the generation of vast amounts of energy for the coming centuries while keeping the amount of waste to be buried less than today's growing stockpile of spent fuel. Also, the reduction of the amount of TRUs in the fuel cycle associated with such advanced system may make the enterprise to secure this material from diversion more manageable especially if this is achieved via regional fuel cycle centers.

Finally, advanced nuclear energy systems based on closed fuel cycles can be realized at a modest cost increase of about 15%, over the cost of existing once-thru fuel cycle. Those systems can be economically competitive with other means of generating energy if the full cost of generating energy, including externalities, is taken into account.

REFERENCES

1. US/DOE, '*Generation-IV Roadmap*', 2002.
2. US/DOE, US-DOE, *Report to Congress on Advanced Fuel Cycle Initiative: The Future Path for Advanced Spent Fuel Treatment and Transmutation Research*, January 2003.
3. D. Wade, R. Doctor, K. Peddicord, *STAR-H2: A Battery-Type Lead-Cooled Fast Reactor for Hydrogen Manufacture in a Sustainable Hierarchical Hub-Spoke Energy Infrastructure*, GENES/ANP 2003, Kyoto, September 15-19, 2003.
4. Centre of Geopolitics of Energy and Raw Materials, *Scenarios of Nuclear Power Growth in the 21st Century*, University of Paris IX Dauphine, 2002.
5. International Institute for Applied Systems Analysis (IIASA) and World Energy Council (WEC), *Global Energy Perspectives to 2050 and Beyond*, WEC, London (1995).
6. Nakicenovic N., Grubler A., McDonald A. (Editors), *Global Energy Perspectives*, International Institute for Applied Systems Analysis (IIASA) and World Energy Council (WEC), Cambridge University Press, Cambridge, United Kingdom (1998).
7. International Atomic Energy Agency (IAEA), *Global Energy Outlook*, Key Issue Paper No. 1, Proc. Intl. Symp. On Nuclear Fuel Cycle and Reactor Strategies: Adjusting to New Realities, Vienna (Austria), 3-6 June 1997, IAEA Proceedings Series, STI/PUB/1026, pp. 11-83, Vienna, 1997.

8. International Atomic Energy Agency (IAEA), *Energy, Electricity and Nuclear Power Estimates for the Period up to 2015*, IAEA-RDS-1/96, IAEA, Vienna (1996).
9. OECD International Energy Agency (IEA), *World Energy Outlook*, 1998 Edition OECD, Paris, 1999.
10. OECD Nuclear Energy Agency (NEA), *Nuclear Energy and the Kyoto Protocol*, Paris, 2002.
11. Luc Van Den Durpel, *Symbiotic Nuclear Energy Systems for a Sustainable Energy Future*, BNS Symposium, November 26, 2003, Brussels.
12. International Atomic Energy Agency (IAEA), *Market Potential for Non-electric Applications of Nuclear En*ergy, Technical Reports Series No. 410, Vienna, Austria, 2002.
13. US-DOE, *National Hydrogen Energy Roadmap*, November 2002.
14. Forsberg Ch., Peddicord K.L., *Why Hydrogen Production from Nuclear Power?*, Proceedings of the American Institute of Chemical Engineers Spring National Meeting, March 12, 2002.
15. L. Van Den Durpel, D. C. Wade, H. Khalil, A. Yacout, *Dynamic Analysis of Nuclear Energy System Strategies for Electricity and Hydrogen Production in the USA*, Global 2003, November 16-20, 2003.
16. L. Van Den Durpel, A. Yacout, D. Wade, H. Khalil, *DANESS – Dynamic Analysis of Nuclear Energy System Strategies*, Global 2003, New Orleans, November 16-20, 2003.
17. MIT, *The Future of Nuclear Power*, July 2003.
18. Harvard, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*, DE-FG26-99FT4028, July 2003.
19. IAEA, OECD/NEA, *Uranium 2001 Resources, Production and Demand*, 2002.
20. C. MacDonald, *Uranium: Sustainable Resource or Limit to Growth?*, World Nuclear Association Symposium, London, September 3-5, 2003.
21. R. Wigeland, T. Bauer, T. Fanning, E. Morris, *Repository Impact of LWR MOX and Fast Reactor Recycling Options*, ANS Winter Meeting / Global 2003, New Orleans, November 16-20.
22. 3. A. M. Yacout, R. N. Hill, L. Van Den Durpel, P. J. Finck, E. A. Schneider, C. G. Bathke and J. S. Herring, "Dynamic Analysis of the AFCI Scenarios," *PHYSOR 2004,* Chicago, Illinois, April 25-29, 2004
23. 2003.US/DOE, Energy Information Administration.
24. EC, EUR 20198, *External Costs: Research results on socio-environmental damages due to electricity and transport*, 2003.